SOME INUNDATIONS ATTENDING TROPICAL CYCLONES

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The rise of water on the coast in advance of a tropical cyclone at sea is frequently termed a "tidal wave." It is sometimes, with greater propriety, referred to as a "storm wave." The use of the word "wave" in either case is opposed by many meteorologists who contend that the rise of water, in any event, is relatively slow until the center of the cyclone approaches closely. It is a subject discussed only superficially in meteorological textbooks. Cline (1) assembled tidal data and explained many of the phenomena of tides and waves in tropical cyclones, concluding that the rise of water along the coast in advance of the cyclone is not a wave in any sense of that term.

The tide, due to astronomical causes, rises only 2 or 3 feet in the open oceans. There it is of little significance; its rise and fall are gradual. When it strikes the coast its range is frequently 10 to 12 feet. In certain bays and channels, where the wave encounters the shores and a risng ocean bed, retardation causes a tide of 25 to 50 feet above low water.

In the estuaries of many rivers vast sand flats are nearly dry at low water, and the tide rises with such rapidity that the wave assumes the shape of a wall of water called a "bore." (2) Tides in the St. Lawrence, ranging from 3 to 4 feet in the gulf, penetrate 450 miles up the river, with a range of 9 to 18 feet, and the rate of propagation up to Quebec, 350 miles from the mouth, is 83 miles per hour. At the mouths of the Ganges and Amazon, the bore is at times very formidable and may, at spring equinoctial tide, with moon at perigee and favorable winds, reach a height of 30 to 50 feet, advancing as a wall of water or series of waves (6).

Thus the astronomic tide, a gradual rise of 2 to 3 feet in the open oceans, is transformed by contact with the coasts and in some situations comes as a wall of water. Its range in certain localities is greatly magnified. The characteristics of this rise and fall of the water are as varied as the contours of the coast lines and the slopes of the ocean beds.

The rise of water with the cyclone is likewise relatively small in the open ocean. Cline (1) estimates it as less than 5 feet in the greatest storms. Certainly that due to reduction of atmospheric pressure is not more than 2 or 3 feet. There are near the center of the cyclone tremendous seas, described by many mariners as rising 30 to 40 feet, not like waves, but huge pyramids of water. The level of the ocean itself, however, is raised relatively little. As the storm tide encounters the shallows and indentations of the coast, it is retarded and the water rises in many instances 10 to 15 feet and probably in exceptional cases considerably more.

It is the object of this paper to discuss a number of inundations attending cyclones and to show that the rise of water exhibits many if not all of the characteristics of the astronomic tide in like situations, including bores and similar phenomena, and that the direction of movement of the cyclone with reference to the coast line, the contour of the coast, and rate of the cyclone's approach and passage are in certain instances responsible for great storm waves that have destroyed hundred of millions of dollars worth of property and hundreds of thousands of lives in the aggregate.

The need of such a study is remarked by Cline, who says: "Concrete information regarding the winds in hurricanes that produce the swells and tides is limited and, therefore, these are subjects that must be investigated in this connection." He does not consider the currents set up by the storm circulation except to note their existence in citing the drift of gas and whistling buoys. We know that the most powerful agent for transferring quantities of water from one place to another is the current, and strong evidence will be presented to show that the currents about the cyclone are sufficient to explain the storm wave.

Aside from wave motion imparted to the ocean surface, the cyclone has three important effects:

(*a*) The winds of the right rear quadrant of the cyclone, in the Northern Hemisphere, with a counterclockwise rotation, are combined with the movement of translation and are the most powerful and of the greatest duration of any of the winds of the cyclone. The contrast of the strength of these winds with those in the other quadrants is probably even greater than indicated by Cline, because his observations are not instantaneous. The data he has assembled are from land stations. As the cyclone moves inland, it loses intensity. Before the winds of the right rear quadrant reach the observing station the cyclone has weakened and these winds are then less powerful than they were at the time the front of the cyclone was passing over the station.

(*b*) The waters are raised by the winds and elevated by the reduction of atmospheric pressure near the center of the cyclone and form a whirling disk or mound which is redeveloped continually as the cyclone moves forward.

(*c*) As a vast whirlwind of great power, the cyclone communicates to the waters a turning movement which is quite pronounced near the storm center. As proof of the power of these currents, Cline cites the fact that two gas and whistling buoys in August, 1915, and three in September, 1919, were carried 2 to 8 miles parallel to the coast. He states that Trinity Shoals gas and whistling buoy, weighing 21,000 pounds, anchored in 42 feet of water with 6,500-pound sinker, and 252 feet of anchor chain weighing 3,520 pounds, was carried 8 to 10 miles westward.

These currents scour away the sand from the coast in great quantities. In 1900, at Galveston, the waterfront moved in several blocks permanently due to the scouring action of the cyclone currents. Where street cars once ran along the beach, the site of the tracks is now well out in the Gulf. These currents moved from northeast to southwest or from right to left across the front of the cyclone. After the cyclone moves inland a reverse current is set up from southwest to northeast along Galveston Island.

There have been several instances of persons clinging to floating wreckage and being carried, after the center of the storm had passed inland, many miles from southwest to northeast along the coast.

Eliot (3) discusses these currents in connection with cyclones in the Bay of Bengal and notes a strong westerly set at the head of the bay characteristic of storms in this position and indicative of storm formation or approach toward the north end of the bay. The excessive drift noted in many instances by Eliot, Piddington (4), and others from the logs of vessels in cylcones is sufficient proof in itself of strong currents about the center of the cyclone.

The fact that the speed of translation of a cyclone is relatively small and its winds violent are evidence that a strong circulatory motion of the waters must be set up.

The very clear evidence that such a current does actually exist makes it all the more remarkable that no one has considered the effect of an obstruction to this flow of water.

When any headland or bay shore is so situated as to impede the progress of this current from right to left in advance of the cyclone, the waters pile up against the obstruction and accumulate in bays and inlets facing into the current either directly or at an angle.

As the center of the cyclone approaches the coast, the whirling motion of the waters become more vigorous with more violent winds. The resistance of shallows near the coast causes the waters in this rotating disk to pile up on the right side of the center of the storm just before it moves inland. All the waters to the left of the center are now carried around the rear of the center and piled up to the right. The tide falls with great rapidity to the left of the center because the return branch of the current in front of the center which has supplied water to the left is now hindered by the shore and shoals.

If there is a bay or inlet to the right of the track of the cyclone center, the waters of this revolving mound are precipitated toward the mouth of the bay or inlet. At that point waters are already accumulated from hours of resistance to the right-to-left current prior to the arrival of the center.

The center of the storm now moves inland, leaving the accumulated waters to be driven by the powerful winds to the rear of the center against the accumulated water at the entrance of the bay, inlet, or river mouth and a storm wave results, driven forward by the most powerful winds of the hurricane.

With a gently sloping bed, this wave is retarded and piled up by resistance. In some favorable cases it takes the form of a wall of water that sweeps everything before it. It is important to note that the displacement of this central mass of water to the right takes place before the storm center moves inland and at the time shoal water is reached. Therefore this pitching of the central mass to the right and its movement with the rear winds can take place in time for the rising waters to be caught in the shift of wind to southeast and south and thus go forward to the right of the center.

The evidences that this action takes place are practically unquestioned, once we have realized the power of this current.

In September, 1900, the cyclone moved to the west of Galveston Bay, the center passing to the left of the city shortly after 8 p. m.

Quoting from the report of Dr. I. M. Cline:

> The water rose at a steady rate from 3 p. m. until about 7.30 p. m., when there was a sudden rise of about 4 feet in as many seconds. I was standing at my front door, which was partly open, watching the water which was flowing with great rapidity from east to west. The water at this time was about 8 inches deep in my residence, and the sudden rise of 4 feet brought it above my waist before I could change my position.

He notes the rapid current from east/west or from right to left in front of the cyclone. The center was then sweeping over a rising Gulf bed to the southwestward and the shore line was rapidly cutting off the return current in front. His residence was located at Twenty-fifth and Q Streets, several blocks from what was then the shore line, and many buildings stood between his residence and the open water. This wave penetrated this section of the city. It was undoubtedly the front of the storm wave. Approximately 6,000 persons lost their lives as this wave advanced.

To produce a storm wave of this kind, the cyclone must move in a direction nearly normal to the coast line. Thus its rotary currents are developed to maximum strength when the storm strikes the shallows near the coast. The wave is then best developed when a headland, island, or other obstruction arrests the rotary movement and there is a bay or inlet to the right for development of the wave.

The highest tides on the coast of the Gulf of Mexico have been developed under such circumstances.

At Corpus Christi, in 1919, the storm center passed to the left of the bay, and the waters reached a height of 16 feet on the left bay shore. The storm moved nearly normally to the coast line.

At Indianola, in 1886, the cyclone moved to the left of Matagorda Bay, in a direction nearly normal to the coast line, and the city was swept away. It was located on the left side of the bay, considered from the point of approach of the storm. The city has never been rebuilt.

At Galveston in 1900 and 1915 the high water was produced by storms moving to the left of Galveston Bay. Galveston is located to the left of the bay entrance and on the northeast end of the island.

In 1915 a severe storm moved inland over southern Louisiana, in a direction nearly normal to the coast line, and the highest tides of record were measured in the left end of the sounds to the right of the Mississippi Delta, and to the right of the storm center.

In July, 1916, the cyclone moved inland to the left of Mobile Bay, nearly normal to the coast line; and Mobile, at the upper end of the bay and to the left, had the highest tide of record, 11.6 feet.

At Tampa, in October, 1921, a cyclone recurved in the eastern Gulf and passed to the left, nearly normal to the coast line. The waters in Tampa Bay, which had been at normal height, rose to 10.5 feet above low water, by far the highest of record.

The tracks of these storms are shown in Figure 1.

The Corpus Christi storm of 1919, the Galveston storm of 1900, and the Louisiana storm of 1915 crossed very closely to the same point, approximately 27 north and 89½ west. One was moving westward, another west-northwestward, and the third northwestward. The tide at Burrwood was between 2 and 3 feet approximately in each instance, evidently somewhat higher in the case of the storm that moved northwestward. However, the water was then banking up on the right of headlands which interfered with the flow from right to left about the center. At 8 a. m. of September 29, 1915, there was a tide of 3.7 feet at Burrwood and at Mobile 2.5 feet. This difference was consistent as the storm approached and the water was not so high to the left of Burrwood, showing that the right-to-left flow was being hindered and the water piled up as it passed around the Mississippi Delta.

Practically all of these tide records show the water piling up to the right of obstructions to its flow. These are separate and distinct effects from that caused by the drive of water from the right rear quadrant of the cyclone described by Cline.

In the Bay of Bengal the conditions along shore are more favorable for tidal waves, especially at the head of the bay. The cyclones are perhaps as a rule more intense than West India hurricanes. The astronomical tide is developed to a much greater extent than in the Gulf of Mexico.

These conditions combine to produce more severe storm waves in India, especially when the time of high water approximately coincides with the arrival of the storm wave. On the coasts of India the storm wave frequently arrives as a sudden rise of water, sometimes as an advancing wall and sometimes as a bore. The only authentic case of record of a bore produced from a West India hurricane was in September, 1926, at Miami. There the highest water occurred with the shift of wind, and in the Miami River the tide came in the form of a bore that left a mass of wreckage from boats that had sought safe anchorage.

Eliot cites several great cyclones in the Bay of Bengal, some of which were attended by pronounced storm waves. The movement of the storm, the shape of the coast line, and other conditions were practically the same as that shown in the case of record water heights in the Gulf of Mexico.

The Calcutta cyclone of 1864.—It crossed the coast line moving in a direction nearly at right angles to the coast, near Contai, to the left of the mouth of the Hooghly. The barometer fell to 28.025 inches and the calm lasted at Contai from 9:45 to 11:00 a. m. The storm wave arrived at the mouth of the Hooghly a little after 10 a. m., high water being due at about noon as the moon was nearly full.

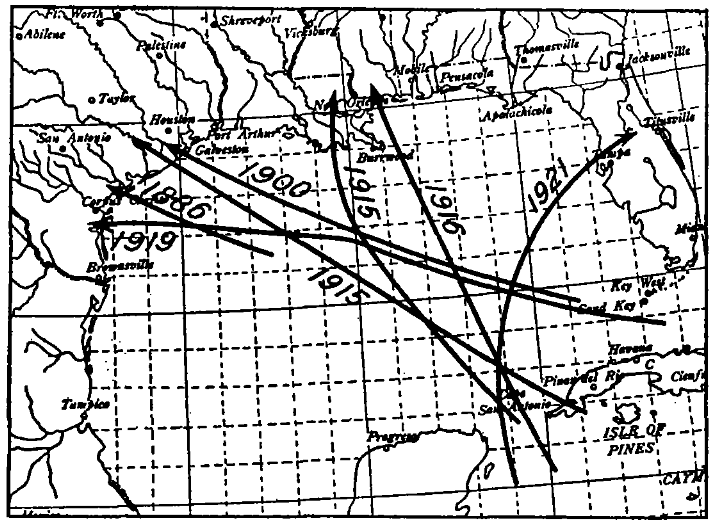
There was an enormous accumulation of water at the northwest angle of the bay, the left side. In the case of a storm there is for some time, as the storm center approaches so as to give a storm wave, a large accumulation of water, according to Eliot, and this head of water finally gives rise to a sudden and overpowering advance of the accumulated mass of water up the river and an almost equally rapid inundation of the lowlands near the seashore. The storm wave is estimated to have risen 40 feet in the Calcutta cyclone. The loss of life from drowning was estimated at 50,000 and from disease as a result of the storm, 30,000. Eliot recites the account of an eyewitness, to the effect that the natives on the coast, whence he was traveling toward Midnapore, informed him that a high bore was to be expected at half past 12. "The water," his informant relates, "all at once suddenly rose as if by magic and steadily rolled towards us."

The Backergunge cyclone of 1876.—The center moved across the bay toward the northeast, passing to the left of Chittagong, and near Bakergunge on the left shore. An enormous storm wave was driven over the islands and lowlands near the mouth of the Megna. There was an unusually high tide, followed very shortly by the storm wave. The pressure of the advancing wave prevented the tidal and river water from flowing off. The storm wave was retarded and finally overpowered the downflowing waters and rushed with irresistible force over the islands and low-lying coastal areas covering them to a depth from 10 to 30 or 40 feet. It was estimated that 100,000 lives were lost from drowning and subsequently 100,000 more died of disease as a result of the inundation. The exact time of the passage of the center of the cyclone and the beginning of the storm wave are not given. Both occurred shortly after midnight with a spring tide.

The False Point cyclone of 1885.—The center passed over False Point Lighthouse, the barometer falling to 27.135 inches. The reading was taken by a trained observer at a land observatory with a properly verified barometer. The wind at the lighthouse at 6:30 a. m. hauled from northeast to northwest, continued to blow a hurricane for a few minutes, then suddenly lulled. The calm lasted till 6:50 a. m., when the wind came with redoubled fury from the south-southwest. The storm wave came up at 6:20 a. m. and swept over False Point harbor, destroying all the houses ashore. It rolled in a wide unbroken wave in a northeasterly direction, submerging villages and carrying away before it, with irresistible force, houses, cattle, human beings, etc. The measured height of the wave at False Point was 22 feet.

Piddington (4) gives descriptions of inundations that have visited Coringa on the Coromandel coast of India. Coringa is located to the right of the delta of the Godavery River. According to these accounts, in December, 1789, during a cyclone, when the high tide was at its highest point and the northwest wind, blowing with fury, accumulated the waters at the head of the bay, the unfortunate inhabitants saw with terror three monstrous waves coming in from the sea. The first, sweeping everything in its passage, brought several feet of water into the town. The second inundated all the low country and the third overwhelmed everything.

In 1839 more than 20,000 persons are said to have perished at Coringa in a storm wave.



Partial tracks of 7 tropical cyclones that created record storm tides on the coast of the Gulf of Mexico. All moved so as to approach the coast approximately at right angles. Record tides were produced in bays and inlets immediately to the right of the point where the center crossed the coast

A number of these inundations have occurred on the low coastal lands of China. One in 1881, at Haifong, in a typhoon, caused the death of 300,000 persons.

As an illustration of the power of the cyclone in driving water around the center: In October, 1910, a cyclone described a loop in the eastern Gulf and finally passed out over southern Florida on the 18th. On that day the tide fell to 9 feet below mean low in the Hillsboro River at Tampa, while on the right of the center, south of Cape Romano, the keys and islands were swept by great waves from the Gulf that reached a great distance inland. The survivors escaped by climbing trees. (5)

The above accounts seem to bear out the statement that the rise of water in the storm inundation is by no means gradual. In many cases the direction of movement of the cyclone, the shape of the coast line, the occurrence of normal high tide at time of inundation, from astronomical causes, and other influences, combine to produce a sudden rise of water which sweeps forward like a great wave and causes immense destruction and great loss of life.

CONCLUSIONS

If the rise of water to the right of the center of a cyclone, on moving inland, is due solely to the driving forward of the winds of the right rear quadrant of the cyclone, there remains no satisfactory explanation of the sudden rise of waters to the right of the center. These winds to the right of the center do not change abruptly either in speed or direction, and even the sudden shift of wind to the opposite or nearly opposite quarter as the center passes will not account for the suddenness of the rise in many cases. It is difficult to understand how this wind, even though in a sudden and violent onslaught, such as occurs in the cyclone, can in so brief a space drive forward such a mass of water. The storm wave sometimes precedes the shift of wind at the rear of the center, and with this explanation it must be assumed that the wave outruns the wind which produces it.

Cline then assumes that the rise is gradual and that there is no "storm wave" or "tidal wave." Clearly, his explanation of the tide, if accepted as offering the only causes of high water, do not include the causes of a storm wave. Yet the testimony of observers and the fact that hundreds of thousands of persons have been drowned in these overflows, seem to be indubitable evidence that the rise is sudden and overwhelming.

But Cline does not assume that his is a full and complete explanation of the tidal phenomena of the hurricane.

Reasons have been advanced for believing that the waters take on a rotary motion, similar to the winds in the cyclone acting upon the water. These currents will be communicated to great depth, setting enormous masses of water in motion, as evidenced by the movement of buoys anchored in water 40 feet or more in depth. The power of this great rotating mass of water is fearful to contemplate when it is obstructed by the coast line and its accumulations are driven by the cyclonic winds.

Near the center the accumulation of water on the right front is relieved by a swiftly flowing current along shore. This current is suddenly impeded and later reversed as the center of the cyclone moves inland and the rear winds come upon it. With great pressure suddenly thrown against this relieving current as the center leaves the rotating mass, there is cause for a more rapid accumulation on the right of the center. All the waters of the rotary disk tend to pile up on the right of the center against the coast line. Far from the center this is a slow process, but near the center, the shorter the diameter of the whirl and the greater the velocity of the current the more sudden and violent will be the onslaught.

When a bay, inlet, or river mouth lies immediately to the right of the point where the cyclone crosses the coast, this mass of water drives forward into the sloping bed and narrowing channel, to be retarded and heaped up. It finally spills over and sweeps forward. These places are frequently harbors for ships and the locations of cities with a considerable population.

ACKNOWLEDGMENT

The author claims nothing original in the way of observation. He has consulted the writings and observations of Weather Bureau officials recorded mostly in the MONTHLY WEATHER REVIEW and numerous additional sources, but chiefly the works of Cline, Eliot, and Piddington.

LITERATURE CITED

(1) Tropical Cyclones, by I. M. Cline.
(2) A Practical Manual of Tides and Waves by W. H. Wheeler.
(3) Cyclonic Storms in the Bay of Bengal, by John Eliot.
(4) Sailor's Hornbook, by R. Piddington.
(5) Monthly Weather Review, October, 1910.
(6) Reclus, Elisee, The Ocean.

THE RELATION OF SPRING TEMPERATURES TO APPLE YIELDS

By W. A. MATTICE

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Apples, while not of such universal need as corn, wheat, and other important food crops, are still of sufficient value to the human race to have rather large areas of certain States devoted to their cultivation. By examining a dot map prepared by the United States Department of Agriculture, it will be found that the heaviest centers of apple production lie in two States, New York and Washington. No other State has the concentration that is found in these, and between them they produce a large proportion of the Nation's apple supply.

The cultivation of apples requires somewhat different conditions of soil, climate, etc., than most crops. While different varieties of apples require longer or shorter growing seasons, in most cases the local conditions or topography must be favorable if a high-producing orchard is to be maintained. One of the most important risks that confront the apple grower is the liability of damage from late spring frosts. Most apple-producing areas of the United States are exposed to this injury and serious losses occur, but the frost hazard in some sections is comparatively small, particularly in the Northeast. Fruit trees respond readily to relatively short periods of warm weather in spring, and when there are rather long periods of warmth, premature blooming is practically certain. In cases of this kind, the late frosts cause greater damage than when the trees are in a less advanced stage, even though the temperatures may be lower in the latter case.

It has long been well known that the location of an orchard is a vital factor in determining its success. A north slope in some cases has been found to be slightly more favorable than other exposures, due to the retarding effect on blooming and thus reducing the liability of damage by frosts. Orchards in pockets are exposed to harm through air drainage, which will often cause extensive injury to bloom or newly set fruit, while a neighboring orchard on a higher elevation may not be harmed. Spring frosts, the amount of precipitation, the summer temperatures, etc., are elements over which the orchardist has no control, but weather influences can often be controlled or modified through improved orchard management.

The inland river valleys of Washington are peculiarly adapted for apple culture, with their comparatively mild climate and long summers. The southern shore of Lake Ontario in New York State is another region which has been largely devoted to the cultivation of deciduous fruits, with the great body of water acting as a deterrent for spring frosts and otherwise moderating the climate. In other States, Virginia and West Virginia are probably the only ones showing such a concentration of fruit orchards, with the Shenandoah Valley famous for its orchards, and especially for the apple-blossom festival which takes place there every year. Conditions in Virginia, again, are such as to promote apple growing on a large scale, with the great valley affording an extensive area sheltered from many climatic severities.

During the summer of 1926 a survey of the apple-producing sections of Virginia, West Virginia, and Pennsylvania was made by the several State experiment stations and the Department of Agriculture with the coop-